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Design Considerations for Sailing Robots Performing Long Term Autonomous Oceanography

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Abstract

Over the last four years we have developed five sailing robots of various sizes with the intention of performing long term ocean monitoring. These have demonstrated that a sailing robot could potentially perform long term ocean monitoring. A number of sensor packages, sail designs and hull designs have been tested. Wing sails have been found to be particularly suitable for this application as they minimise potential points of failure. Work with biologically inspired control systems that are capable of adapting the robot's behaviour to its conditions and the demands of its mission is currently ongoing.

1. Introduction

Since 2004 the authors have built five sailing robots varying in size between 50cm and 3.5m long, with the aim of performing long term autonomous oceanographic monitoring. Given that sailing robots can be deployed in a more flexible manner and at potentially lower cost than existing ocean monitoring systems such as data buoys, survey ships and satellites, it is hoped that they will supplement or even replacing these systems. Prior to the construction of their first boat the authors are aware of only three previous attempts to build sailing robots these are by Abril, Salom and Calvo (Abril and Calvo, 1997), Ross[1] and Elkaim (Elkaim, 2002). All of these focused on building proof of concept robots and illustrating their ability to sail a pre-determined course, however none appears to have continued their work or attempted to tackle many of the problems associated with maintaining long term autonomy of a sailing robot.

[1] `http://www.cs.cmu.edu/~br/CbotWeb/rb98.html`

2. Robot Specifications

2.1 AROO

AROO (Autonomous Robot for Ocean Observation) (Neal, 2005) was constructed in late 2004 as a proof of concept for a small but reasonably durable sailing robot. The plastic hull is 1.5 metres long and the sail isa 1 metre aluminium wing sail driven by a 2 rpm by a reduction gear DC electric motor mounted inside the hull at the base of the mast. Rudder control is provided by a single servo. AROO has only three sensors, potentiometers to detect wind direction and sail position and a magnetic compass. These are connected to a Basic Stamp microcontroller and then via a serial port to a Jornada 720 which runs the higher level control algorithms and allows remote access via the wireless network card allowing remote access at distances of 10s of metres. AROO's power source is a 4.2Ah 12V lead acid battery, providing up to 36 hours of operation depending on the frequency of actuator use. AROO was only ever tested in a small lake demonstrating the concept of a sailing robot. In particular it demonstrated the feasibility of a wing sail in both light and strong winds. Problems with control system response time, compass precision and manouevrability sometimes resulted in wild oscillations in the boat's course.

2.2 ARC

ARC was constructed in early 2006 and aimed to rectify many of the mistakes made in AROO (Sauze and Neal, 2006) and to introduce as much redundancy as possible. It features a similar length, but more stable plywood hull, two rudders (controlled by a single actuator), two independently controlled sails, a gimbaled compass, GPS receiver and initially a combination

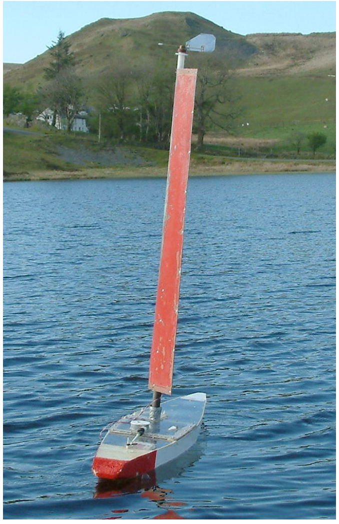

Figure 1: Aroo during a test on a lake in April 2005.

Figure 2: ARC during the 2006 Microtransat Challenge.

of an AtMega128 microcontroller and a Gumstix [2] single board computer running linux. The AtMega was later removed in favour of controlling everything from the Gumstix. ARC uses three stepper motors for sail and rudder control. The use of dual sails provides redundancy in steering, as the sails can be set to provide directional control. Additional redundancy is provided by the three stepper motor controllers each of which can control two of the three motors. Initially no feedback of motor position was given, but feedback potentiometers have since been included due to positioning problems. ARC is powered by 20 1.2 volt, 2500 mA/hour NiMH AA rechargeable batteries which are connected in two banks of 10 to provide 12 volts and a peak current of around 4 amps.

[2] www.Gumstix.com

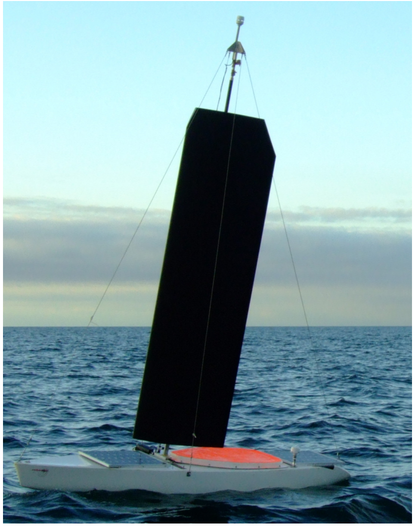

Figure 3: Beagle-B during the 2007 Microtransat Challenge.

2.3 Beagle-B

Beagle B was constructed in late 2006 by Robosoft (a French robotics company) and is intended to provide a reliable oceanography platform. It is 3.5m long, with a 4m carbon composite wing sail, two 15 watt solar panels and four 12V 60Ah lead acid batteries. It includes a tilt compensated flux-gate compass, ultrasonic wind sensor, GPS, Iridium Short Burst Data transceiver and GM-862 GSM modem, two LA12 linear actuators for rudder and sail control and a YSI 6600 Sonde [3] for gathering oceanographic data. The whole system is controlled by a pair of Gumstix single board computers, one for the control of the robot and one for the oceanography sensors and communications. Beagle-B participated in the 2007 Microtransat Challenge[4] and during summer 2008 it will be deployed to measure water quality in Cardigan Bay off the west coast of Wales. Beagle-B again demonstrated the efficacy of the wing sail design by frequently out running yachts being used to chase it, in particular during light winds when traditional sails on the chase boat collapsed.

2.4 Pinta

Pinta is our latest boat and unlike the previous boats is built with the intention of racing. It will be taking part in the 2008 World Robotic Sailing Championship and Microtransat transatlantic race. It is based upon a Topper Taz [5] sailing dinghy and unlike our other boats it uses a single traditional sail controlled by a DC electric motor and a winch. Its design uses the same model

[3] `https://www.ysi.com/portal/page/portal/YSI_Environmental/Products/Product_Family/Product?productID=EMS_SON00_6600V2`

[4] http://www.microtransat.org/2007.php

[5] http://www.toppersailboats.com/taz.aspx

Figure 4: Pinta under construction in January 2008.

compass, ultrasonic wind sensor, GSM modem, satellite transceiver and a similar motor controller as beagle B. Its rudder is controlled by an off the shelf auto-helm, this simplifies the control system dramatically as only a target heading needs to be provided to it. Power is provided by 6 solar panels providing a peak of 120W and 16, 12V, 7Ah lead acid batteries located inside the hull to provide extra ballast.

3. Design and Construction Lessons

3.1 Choice of Computers

When evaluating the type of computer to use five possibilities emerged:

1. A traditional microcontroller such as a PIC, AVR or 68HC12.
2. An "easy to use" microcontroller such as the Basic Stamp, OOPIC or PICAXE.
3. A single board computer or PDA running an operating system such as Windows CE, VxWorks or Linux and using a processor targeted at embedded applications such as an ARM, MIPS or AVR-32 processor.
4. An embedded x86 PC running a full operating system such as Windows XP, Linux or FreeBSD. There are many specialist motherboards and processors targeted at embedded applications such as the PC/104 and Mini,Nano and Pico ITX motherboards and the AMD Geode, Via C3/C7 and Intel Atom processors.
5. A combination of the above or multiple computers.

AROO was developed as a split system, placing low level operations such as actuator positioning and reading sensors on a Basic Stamp microcontroller which communicated with a Linux based PDA via a serial port. This proved to be a poor choice due to latency and the Basic Stamp's inability to multi-task. In developing ARC initially only a single microcontroller was used to control two sail and one rudder actuator, not wanting to repeat easrlier problems a method was required to multitask during actuator movement. The solution was to place the motor handling code inside an interrupt handler which was triggered by the timer interrupt at regular intervals, thus allowing other processes to continue. This approach brought latency levels into a range of less than 10 milliseconds which was more than acceptable, unfortunately using interrupts in this way brings with it a number of complexities and requires significant programming effort. The alternative approach which was considered was to use a series of microcontrollers each responsible for only a single sensor or actuator with a central co-coordinator requesting sensor data or actuator movements from the others. This approach was not followed as it was considered to add significant programming and hardware complexities in addition to a fear or repeating the same problem seen in AROO.

A decision was later taken to replace the microcontroller with a Gumstix single board computer. The Gumstix runs a slimmed down version of linux known as uCLinux, but still offers all the advantages of an operating system such as processes and threads, filesystems, device drivers and network stacks. As the Gumstix lacked sufficient I/O ports to control 3 stepper motors a general purpose I2C I/O extender chip was installed on each of three stepper motor controllers. It is also worth noting that while the latency of the Gumstix is low enough to provide direct control of stepper motors it would not be low enough to directly control a servo or DC motor.

As uClinux provides locking and threading support the interrupt handler code could be dramatically simplified into a few threads. The eventual design was to split the program into a series of threads to gather wind sensor, GPS and compass data and to control rudder position with respect to desired heading and sail position with respect to wind direction. Common data such as wind direction, current location, the current waypoint, heading and distance to the next waypoint, current heading, rudder position and sail position were all stored in global variables which could be locked during updates or reads to produce fully atomic operations.

The use of an operating system speeds development time somewhat as there is no need to load new programs into microcontroller EEPROMs or to reboot when a new program is ready. The use of Linux is of significant help as it allows remote login to the system over the network. Additionally there is the potential to even compile code directly on the robot, however due to memory constraints of the Gumstix this technique is not currently being used.

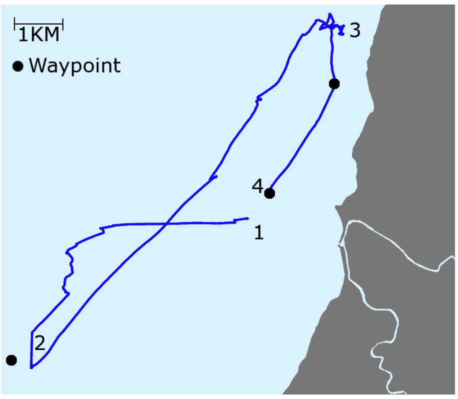

Figure 5: The route taken by Beagle-B during the 2007 Microtransat. Point 1 is the start, at point 2 the robot crashed due to a faulty power switch, at point 3 the wind dropped and the boat struggled against a strong tide, at point 4 the robot reached its final waypoint.

The Gumstix in ARC proved to be highly successful, easing the complexity of the software and speeding up the development process significantly. As a result this architecture has been copied in Beagle-B and Pinta.

3.2 Navigation Algorithms

The control software of ARC, Beagle-B and Pinta share a common base differing only to accommodate hardware variations. At present the implementation of the navigation system is simplistic. Waypoints are loaded into the program, the distance and heading to the next waypoint are calculated and fed into the course holding routines which adjust the rudder. A waypoint is considered to be reached when the boat passes within 50 metres of it. In the event of overshooting a waypoint the boat will end up turning back towards the waypoint in order to reach it. It is intended that for ocean sailing waypoint tolerances may be increased. The current control system makes no attempt to compensate for or avoid currents, tides, bad weather or the affects of the boat tilting. Despite this, the system still appears to function well with Beagle-B having successfully sailed over 25km in a single mission, as shown in Figure 5. A more extensive system is required for long term autonomy, but is beyond the scope of our current work.

3.2.1 Tacking and Jibing

The control system has no awareness of a tack or jibe (turning the boat through the wind), the steering system simply follows the desired heading which is the heading to the next waypoint. If the course is not directly sailable (e.g. it is 45 degrees +/- the wind direction) then the desired heading is adjusted to 45 degrees from the wind direction and this course is followed until the desired point becomes directly sailable. Many human sailors would favour zig-zagging into the wind rather than taking this single tack approach. This approach does have one potential problem, if operating near to the coast it is quite possible that the boat would attempt to sail into the shore when its course was not directly sailable. AROO took a totally different approach as it had no GPS so could not generate a desired heading to a waypoint, it instead would time alternate tacks and sail in zig-zag fashion. This algorithm was shown to work correctly in simulation, but was never tested in the the real world.

3.3 Power Systems

3.3.1 Power Switches

Early in the development of AROO the need to easily switch the entire system off was demonstrated when a program did not run as expected causing the sail to be left rotating with a wire wrapped around it placing the sail actuator under considerable strain and draining the battery rapidly. Until this point the only power switch had been inside the boat and required a deck hatch to be unscrewed in order to access it, this kept the switch waterproofed but prevented the robot from being switched off without first being on land and then taken apart. A magnetic switch was later installed and worked reasonably but was far from 100% reliable. For ARC a mechanical switch was placed on the deck inside a small plastic box who's lid was screwed on and sealed with silicone. This was easier to access than AROO's but still took over a minute to gain access. With Beagle-B this problem was believed to have been solved with a waterproof key based switch located on the deck. Unfortunately it turned out this only turned off power from the batteries and not from the solar panels. Under well light conditions this would leave the computer running and occasionally allow actuators to move, however the solar controller would often cut power when the sun was obscured by cloud or shadows. To make matters worse the switch was not completely waterproof and began to randomly cut the power, this was later found to be due to salt deposits forming inside it. This development has shown the clear need for a properly waterproofed, externally accessible power switch which will turn off everything.

3.3.2 Choice of Battery Types and Solar Panel

The choice of power system has a significant impact on the weight, lifetime and cost of a sailing robot. If long term operations are to be achieved then the obvious choice is to use photovoltaic solar panels to charge batteries during the day and batteries to power the robot at night. In this case the battery must be able to hold sufficient charge to power the robot through the night and preferably for several days should bad weather reduce solar panel efficiency. An alternative approach could be to simply power the robot with batteries, although this would limit mission lengths to a few weeks at best, however for many applications this may still be sufficient and will lower manufacturing costs.

In designing AROO and ARC this approach was taken as they were not intended to spend prolonged periods of time at sea and solar panels would have added complexity to the electrical systems. The choice of a lead acid was mainly due to the availability of spare batteries from other projects. ARC made use of rechargeable AA NiMH batteries which provide a higher energy density than lead acid's and their shape and size allow them to be placed in the keel for ballast (which also frees space elsewhere), they are also relatively cheap, easily available and if required individual cells can be replaced. Beagle-B and Pinta both use lead acids because of their durability, low cost, low self-discharge rates and ability to deliver high peak currents. Again the batteries have been placed at a low point in the hull to provide ballast.

Various configurations for solar panels are possible. In Beagle-B the approach has simply been taken to place solar panels flat on the deck, whereas Pinta has opted for placing panels on an angled frame (which can been seen behind the boat in figure 4). As Pinta's sole task is to cross the Atlantic from east to west, the idea of an asymmetric configuration with more solar panels on what for the majority of the journey will be the south facing side has been considered.

3.3.3 Power Budgets

With Beagle-B the peak output of the solar panel is 30 watts, in reality this results in an average output of 10-15 watts during daylight hours and given 12 hours of daylight this would give an average output of 5-7.5 watts, at a latitude of 60 degrees in winter this would be nearer 6 hours and 2 watts. Figure 6 illustrates the power budget of Beagle-B and shows that just to run the robot requires an average of approximately 1.7 watts, leaving between 0.3 and 4.8 watts to run scientific instruments depending on lighting conditions. Given these constraints it is desirable to be able to switch off every sensor when not in use, to enter sleep modes on the computers and keep actuator use to a minimum. One feature of Beagle-B which aids this is its ability to sail for several hours without major actuator movements, during the 2007 Microtransat Race there were several times when the chase boat believed the computer had crashed as they had observed no rudder or sail movements. Given this actuator duty cycles can be kept to a minimum of say 1% or 36 seconds of actuator movement per hour. Sensor duty cycles can also be kept to a minimum once a stable course is established as there is no need to be sampling the GPS, compass or wind sensor more than a few times per minute perhaps at a 5% duty cycle or 3 checks per minute. Experiments

Name	Power	Duty Cycle	Average
Gumstix (x2)	2W	25%	0.5W
Wind Sensor	0.5W	5%	0.025W
Compass	0.5W	5%	0.025W
GPS	0.5W	5%	0.025W
Iridium Transceiver	1.75W	0.15%	0.0026W
Actuators (each)	60W	1%	0.6W
Total			1.7776W

Figure 6: The power budget for Beagle-B excluding any scientific sensing payload. The power column refers to the peak power consumption of the device when in use, duty cycle to the percentage of time it will be on and average to the average power consumption given the duty cycle into account.

with ARC demonstrated that it was actually able to correct its course without any intervention from the control system even when it was spun 180 degrees off course.

Obviously there are scenarios when the user might wish to be less cautious with power management, for example where station holding or higher frequency sampling is required. Another consideration is that given Beagle-B has 2880 watt hours of battery, a week long mission powered entirely by the batteries and and using an average of 10 watts (or 20 watts if its reasonably sunny) is not infeasible. It would also be possible to spend a week sailing to a site of interest on a minimal power budget, then perform ocean sampling for a week nearly draining the batteries and then to sail back home again on a minimal power budget.

3.3.4 Intelligent Power Management

As demonstrated in section 3.3.3 there is little power to spare. Clearly there is a need for advanced power management systems. A simple approach might be to allow the operator to control the maximum duty cycle for any piece of equipment. However a more flexible system which is more in keeping with the idea of an autonomous vehicle is desirable, there are also many situations other than power management where it is desirable to modify the behaviour of the robot in response to changing conditions, for example an actuator overheating.

One potential strategy is to borrow inspiration from biological systems, which are capable of maintaining a stable state despite fluctuations in both their internal and external environments. A key contributor to this ability is the endocrine system which secretes chemical messengers known as hormones into the bloodstream, these rapidly reach virtually all cells in the body, upon reaching a cell they may bind with the cell, providing the cell has an appropriate receptor. Upon binding the hormone will either suppress or promote certain behaviours of the cell. The endocrine system does not act in isolation, the release of hormones is often the result of a trigger from the neural or immune systems and this in turn forms part of a wider feedback loop. This idea has been considered by many computer scientists to date(Arkin, 1992, Parisi, 2004), but has rarely been implemented beyond simulation. Such a system would allow many parameters to be included and for the robot to continuously adjust its behaviour between competing demands. This removes the need for complex sets of rules to ensure the correct behaviour is selected.

3.4 Actuators

So far three types of electrical actuator have been used to control our sailing robots' rudders and sails: standard DC electric motors, stepper motors and servos. Servo's offer the advantage of being easy to position and being able to hold a specified position, however they suffer from a major drawback in that in order to maintain position they must continue to draw power. This was observed in AROO where rudder position was servo controlled, as a result they have not been used in any boat since. AROO used a DC motor for sail positioning and a (non-linear) potentiometer for position feedback, however accuracy was limited and the control system had no control over motor speed. Although this was an extreme case of simple hardware built from scrap components it demonstrated the difficulties of using a standard motor and the need for accurate feedback. Beagle-B's use of an integrated actuator and linear potentiometer coupled with a variable speed motor controller demonstrated that standard motors can be used successfully. Given the bad experience with standard motors and servos in AROO, ARC made use of stepper motors for both its sail and rudder actuator. These were found to be highly repeatable and accurate when tested in the lab under no load, it was perfectly possible to position them correctly without feedback. However when used for real, the sails in particular did not move consistently as a result of the force from the wind. To overcome this feedback potentiometers have since been added. Experience with various motor controllers have also highlighted the need for large heatsinks and realistic testing regimes before deployment.

3.5 Communications

In the development of four robots a number of different communication strategies have been tested including IR, serial ports mounted in the deck, wifi, GSM modems and satellite transceivers. AROO featured an RS232 serial port connector in the deck for reprogramming. This proved quite impractical as the port had to be waterproofed by bolting a cover over the port and sealing it with putty, a process which took several minutes. Infra Red communications were utilised in AROO as this was the only method available on the Psion PDA, the deck is clear acrylic which allows light to pass through. In order to communicate, another PDA had to be placed in a specific spot in which it was very difficult to type or read the screen. This approach was quickly abandoned and the Psion was replaced with a more powerful Jornada PDA with a PCMCIA wifi card. This approach worked reasonably well and distances of over 100 metres were obtained. As these tests took place outdoors no access point was available so a peer to peer ad-hoc network was formed, unfortunately 802.11 ad-hoc mode has a quirk of forming a unique cell id for each network. It was found that a node would attempt to join any networks it found when the network card was initialised and if none were found it would form its own, thus if two nodes went out of range from each other that one of them would then form itself into a new network and when it came back within range of the first node they would no longer communicate without user intervention. The effective result was that once the boat had gone out of range from the laptop communications could not be regained without restarting the network card. Initially in the development of ARC, an access point was carried around with the robot, later it was found that the network card in ARC (a Prism2 compact flash card) was capable of emulating an access point. This approach has been copied in Beagle-B and Pinta. As the wireless card is under the deck with no external antenna the range is short but sufficient to load software or monitor the robot from a chase boat close by.

3.5.1 Teleoperation

ARC and AROO lacked any teleoperation ability as they were operated in calm inshore waters or inland lakes and were relatively easy to pickup with a chase boat. However Beagle-B's size required non-autonomous operation while being towed through a narrow harbour entrance. A teleoperated mode was developed which allowed a user to control the rudder and sail positions from a wifi enabled PDA. This worked reasonably well to make minor adjustments while towing but was virtually unusable for sailing the boat: the user was often unable to observe the rudder movements and had no idea what position the rudder was in; the teleoperation program operated via a secure shell (SSH) connection and this added a significant latency and the wifi connection would frequently fail due to the distance between the operator and the robot or waves obscuring the line of sight between them. Standard radio control equipment was also tested, but still suffered from problems of rudder visibility.

3.5.2 Telemetry and Remote Monitoring

A robot gathering oceanographic data over long periods of time would ideally transmit this data back regularly: both Beagle-B and Pinta are equipped with an Iridium

9601 Short Burst Data transceiver which is able to transmit messages of up to 205 bytes and receive messages of up to 135 bytes. The transceiver is able to perform a full send and receive cycle within less than 90 seconds consuming a peak of 1.5 amps for just a few seconds. This is ideal as it allows power consumption to be kept to a minimum. Both boats are also equipped with a GSM modem for use in coastal waters as it is significantly cheaper than Iridium. Software is currently being developed to store all transmitted data in a database and to provide an interactive map interface to illustrate the robot's position. Eventually this will be a two way interaction allowing for new waypoints or mission objectives to be uploaded.

3.6 Sensors

GPS has been found to be highly reliable on all three robots equipped with it (ARC, Beagle-B and Pinta). There were some initial fears that swaying of the boat or waves passing over the GPS antenna would disrupt reception, but these have proved to be unfounded. Compasses proved to be more problematic, AROO used a CMPS03 magnetic compass, however it was not tilt compensated and errors were induced as the boat rolled, triggering problems for course holding. The same compass was reused in ARC, however it was placed on an aluminium arm which allowed it to swing horizontally, this virtually eliminated the errors in the compass readings. Both Beagle-B and Pinta used a Furuno PG-500 Fluxgate compass which provides automatic tilt compensation, these have operated almost flawlessly. One downside of the PG-500 is that it is unable to provide any tilt information, something which many other tilt compensated compasses provide and which could be of use in optimising sailing algorithms.

AROO and ARC both determine wind direction with potentiometers attached to a vane. This approach generates some level of noise, but readings can be averaged to reduce this. There is concern that they will not survive prolonged ocean conditions, for this reason Beagle-B and Pinta have "no moving parts" ultrasonic wind sensors. These have been found to be highly accurate, except in light winds where swaying of the boat in the waves can generate more airflow than the wind. Despite their accuracy there is still some level of noise, therefore there is still a need to average the readings.

3.7 Sail and hull design

Beagle-B, ARC and AROO all demonstrated the feasibility of wing sails. These offer several advantages over traditional sails, as discussed by (Elkaim, 2002) they maintain their shape in light winds when traditional sails would collapse, can sail closer to the wind and suffer from less drag. Additionally in the context of a sailing robot they are less failure prone as there are no ropes which could snap, jam or become entangled. However three major drawbacks have been encountered. Firstly in ARC and AROO the sails were driven by actuators inside the hull, this required a hole in the deck and has the potential to leak. Beagle-B's design solved this by placing a waterproof actuator on deck and running a power cable into the hull. The second and perhaps more serious problem is that all three boats use rigid sails which cannot be reefed to reduce their size in high winds. Finally the wing sail is not particularly stable when sailing downwind (running), particularly on single sail boats. As this is the least stable point of sail it may be advisable to sail on a broad reach instead and tack downwind.

4. Future Work

To date we have demonstrated the feasibility of a sailing robot as a possible oceanography platform. Work is currently ongoing to perform a long term test mission during which actual ocean data will be retrieved. A number of engineering issues have been highlighted with many more expected to arise during longer missions. Future work will needed to address the durability of the robot, to ensure it can survive prolonged periods at sea. Additional work on power management strategies is also required to maximise the amount of power available to running oceanographic instruments. It is hoped that biologically inspired approaches will aid in this. The end goal is that a robot should be able to remain at sea for several months without intervention from its operators.

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